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Early planting and relay cropping: pathways to cope with heat and drought?

Nuttapon Khongdee [a], Thomas Hilger [a,*], Wanwisa Pansak [b], Georg Cadisch [a]

[a] *Institute of Agricultural Sciences in the Tropics (Hans-Ruthenberg-Institute), University of Hohenheim, Stuttgart, Germany*
[b] *Department of Agricultural Science, Faculty of Agriculture, Natural resources and Environment, Naresuan University, Phitsanulok, Thailand*

Abstract

Maize (*Zea mays*) is an important food and cash crop of uplands in Southeast Asia, where it is often prone to drought and heat stress associated with climate change. This study aimed at assessing the effect of heat and drought on maize performance, testing coping strategies under such weather extremes, and understanding associated mechanisms. The experiment was carried out during 2018 in Thailand, using a split-plot design with three replications. Treatments were: July-planted maize sole cropping (control), July-planted maize-mungbean (*Vigna radiata*) relay cropping, and June-planted maize sole cropping. High temperatures and dry spells during July-August 2018 decreased maize growth strongest in the control and less so in maize relay cropping during generative growth stages, but not in June-planted maize sole cropping. Stress reduced maize nitrogen nutrition index by 40 %. Relay-cropped maize had a significantly higher potential to keep stomata open (320 mmol m^{-2} s^{-1}) than sole-cropped maize (100 mmol m^{-2} s^{-1}). $\Delta^{13}C$ of maize grains confirmed that June-planted maize (-9.43 ‰) was less affected by dry spells and heat stress than July-planted sole cropped maize (-10.23 ‰). Under relay cropping, the latter showed less water stress ($\delta^{13}C$: -10.12 ‰) compared to sole cropping and a higher soil water use. Maize was better able to cope with heat and drought stress when relayed-cropped, although less compared to early-planting of maize. Hence, the tested coping strategies are able to mitigate heat and drought effects on maize growth, while improving food security and crop diversification when relay-cropped with mungbeans.

Keywords: Abiotic stress, climate change, erratic rainfall, escape strategies, Southeast Asia

1 Introduction

Variable weather conditions are severe challenges to rainfed crop production. Heat and drought are, nowadays, common problems across the world, decreasing crops' productivity substantially (Alexander *et al.*, 2006). Weather data provided by the Thai Meteorological Department indicate increased incidence of dry spells during the rainy season with increasing temperatures. Maize (*Zea mays*) is one of the five major crops of Thailand, occupying a large portion of farmland in uplands of Thailand (Ekasingh *et al.*, 2014).

Under rainfed conditions, heat stress and poor water supply limit maize growth and development, thereby decreasing its biomass production (Leipner *et al.*, 1999). Large yield losses are linked with even short periods of high temperature (Reynolds *et al.*, 2015). In the transition between vegetative and generative growth, maize is highly sensitive to drought and high temperature (Edmeades *et al.*, 2017). If extreme conditions occur during this period, the source-sink relationship is imbalanced. Water deficits and high heat, especially during pollination and grain filling, influence this relationship negatively (Setter *et al.*, 2001; Borrás *et al.*, 2002). Fischer *et al.*, (2019) showed that droughts did not only decrease maize yields but also nutrient transport within the plant and their allocation to plant organs, particularly when droughts are severe and happen during sensitive growth stages, e.g. maize tasselling.

Across sub-Saharan Africa and Asia, traditional maize cropping systems were modified to maintain productivity by intercropping or rotating maize with legumes to reduce abiotic and biotic environmental stress (Reynolds *et al.*, 2015). The use of legumes in intercropping may comple-

* Corresponding author–e-mail: thomas.hilger@uni-hohenheim.de

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ment or replace fertiliser inputs (Garg & Geetanjali, 2007). He *et al.* (2012) showed that maize-soybean intercropping leads to positive alterations of microclimate, especially of light intensity, relative humidity and temperature. It also increased grain yield and yield components of maize. Studies from Thailand reported increases of maize yields by maize/legume relay-cropping compared to maize sole cropping (Ongprasert & Prinz, 2004; Punyalue *et al.*, 2018). Other studies stated that benefits of legume relay-cropping include weed control (Gomes *et al.*, 2007), positive effects on soil fertility (Wang *et al.*, 2015) and erosion control (Tuan *et al.*, 2014).

However, there is still lack of proper coping strategies and knowledge on how mitigation effects under climate variation in rainfed upland areas work. This study looks at coping strategies for weather extremes in hillside maize cropping and the mechanisms involved. We hypothesize that the integration of mungbean into maize cropping buffers heat and drought stress on maize yields, associated with an improved microclimate and water infiltration due to a better soil cover and rooting. The objectives of the present study were (i) assessing the effect of high air temperature and drought on growth and yield responses of maize, (ii) testing early planting and relay-cropping as coping strategies for heat- and drought-prone areas, and (iii) identifying associated altered physiological and soil moisture conditions under relay-cropping.

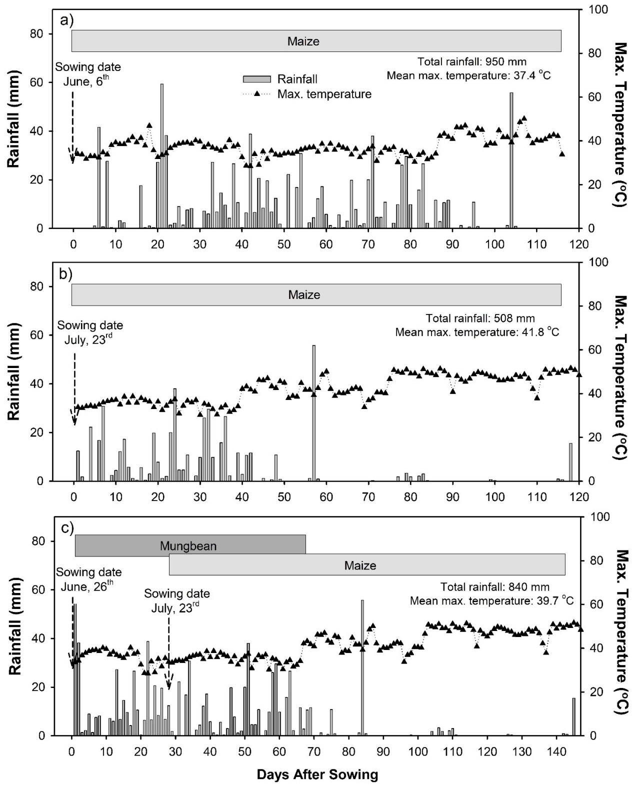

Fig. 1: *Weather details of the tested cropping systems: (a) June-planted maize sole cropping, (b) July-planted maize sole cropping (control), and (c) July-planted maize relay-cropping. Data were collected during 2018 at Wang Thong district, Phitsanulok, Thailand (on-site).*

2 Materials and Methods

2.1 Study site

The experiment was carried on a farmer's field during 2018 at Wang Thong district, Phitsanulok province, Thailand (16°54′21.6" N 100°32′31.2" E), previously cropped with maize. The experimental site has a tropical monsoon climate and is located at an altitude of 209 m above mean sea level. Rains are mainly falling between June and October. In 2018, the annual rainfall was 1365 mm and the mean maximum air temperature was 37.3 °C. The amounts of rainfall received by the three cropping systems - June-planted maize sole cropping, July-planted maize sole cropping (control), and July-planted mungbean (*Vigna radiata*) – maize relay-cropping, where mungbeans were already planted in June (hereafter referred to July-planted maize relay-cropping) - were 950, 508, and 840 mm, respectively. The mean maximum temperatures during the growing period were 37.4, 41.8, and 39.7 °C, respectively (Fig. 1). During 2016, 2017 and 2018, June was always a humid month, whereas September and October were rather dry as indicated by the Standardized Precipitation Index (SPI) (Suppl. Mat. Fig. 1).

The soil is characterised as a loamy-skeletal, siliceous, isohyperthermic kanhaplic Haplustult (Soil Survey Staff, 2014), having a soil organic matter content of 1.5 % and a pH(H_2O) of 4.9. The available P was 14.7 mg kg^{-1} and exchangeable K amounted to 69.6 mg kg^{-1}. Further details of soil data are presented in Suppl. Mat. Tab. 1.

2.2 Experimental setup and data collection

The experiment was setup as a split-plot design with slope position as main factor (top, middle and bottom), coping strategy (June-planted maize sole cropping, July-planted maize relay-cropping, and July-planted maize sole cropping (the later representing farmer's practice or the control) as sub-factor, and three repetitions. Plot size was 4 m by 18 m.

Syngenta 6248, a drought resistant, high yielding maize variety with a growth cycle of 105 days, and Chai-Nat 84-1, a drought resistant mungbean variety with a growth cycle of 65 days, were used for sowing. Before sowing, mungbeans were inoculated with a *Rhizobium* strain developed by Ministry of Agriculture of Thailand. July-planted maize was sown on July 23rd, 2018, June-planted maize on June 6th, 2018, currently coinciding with the first major rains of the rainy season (Fig. 1).

The spacing of maize was 25 cm in the row and 75 cm between rows. In the maize relay-cropping arrangement, mungbeans were sown on June 26^{th}, 2018, 27 days before sowing maize. Mungbeans were planted in double rows at a spacing of 10 cm in the row and 15 cm between two mungbean rows. Distance to maize rows was 30 cm. Both crops were established with minimal soil disturbance by opening a small strip for the seeds. Weeding was done manually with a hoe. June-planted maize was harvested mid of October and July-planted maize at the end of November.

Fertilisers were split-applied to maize with a basal dressing of 24 kg ha^{-1} of NPK as a compound fertiliser (15-15-15) at maize planting and a top dressing of 86.25 kg ha^{-1} of N as urea (46 % N) at 27 days after maize sowing (DAS). Mungbeans received 12.5 kg ha^{-1} of N, 37.5 kg ha^{-1} of P, and 37.5 kg ha^{-1} of K applied as compound fertiliser at sowing as per recommendation. Leaf N status was measured by using a SPAD-502 meter (Konica-Minolta, Japan) on the most developed leaf ($3^{rd}/4^{th}$ from the top) of eight selected maize plants in each sub-plot. Measurements were carried out in 7- to 10-day-intervals from 27 until 55 DAS (n = 5). Optimum N uptake was calculated based on the Nitrogen Nutrition Index (NNI):

$$\text{NNI} = [(\text{SPAD reading} \times 0.04) - 0.64]$$

where NNI $\geq$ 1 indicates optimum N uptake by maize leaves, NNI < 1 indicates low N uptake by maize leaves (Zhao *et al.*, 2018). Maize stomatal conductance was measured twice on 24 and 60 DAS on the same plants selected for the SPAD readings by using a SC1-Leaf Porometer (Decagon Devices Inc., Pullman, Washington). In each sub-plot, all maize plants were harvested and separated into leaves, stems and cobs to determine their fresh weight. Well-mixed sub-samples of all aboveground plant parts were prepared, oven-dried at 65 °C until constant weight was reached, and weighed to obtain dry weights for calculating aboveground biomass (AGB). Maize grain yield and yield components (ear length, 100-seeds-weight, seed number/ear) were assessed for treatment comparisons. In addition, harvest index (HI) was calculated as follows:

$$\text{HI} = \text{Grain yield} / \text{Total aboveground biomass at physiological maturity}$$

Mungbean yield and biomass were also determined. Thereafter, the harvested stover of mungbeans was immediately after its assessment returned to the respective plots and spread between maize rows as mulch to provide additional soil cover during maize cropping and soil organic matter to the soil. Similarly, maize stover was returned to the each plot after harvest.

Weather data were collected by an automated weather station (TLEAD, model AW02, China) on-site. In addition, 15 soil moisture sensors (10HS Sensor, Decagon Devices, Pullman, Washington) connected to a data logger (EM-50, Decagon Devices, Pullman, Washington) were placed in both July-planted maize systems at a soil depth of 10 cm along the slope to monitor the volumetric water content, assessed at hourly intervals.

2.3 Carbon stable isotope evaluation

The carbon isotope discrimination method described by Hussain *et al.* (2015) was used to assess effects of water stress. For this purpose, maize grain samples of each sub-plot were oven-dried at 65 °C until constant weight was reached. Finally ground maize grain flour samples were analysed using an Euro Elemental analyser coupled to a Finnigan Delta IRMS to determine grain $^{13}C/^{12}C$ ratios. δ13C (‰) was calculated by expressing the measured ratios (R_{sample}) against IAEA Vienna standards, $USGS-40$ and $USGS-41$ ($R_{IAEAstandards}$):

$$\delta^{13}C_{sample} = [R_{sample}/R_{IAEAstandards}] - 1 \times 10^3$$

2.4 Data analysis

The obtained data were analysed by the ANOVA method, using SPSS-17 software (IBM SPSS Statistics, Armonk, NY). The difference between treatments means was compared by using the least significant difference (LSD) test at 95 % level of significance. Pearson correlation was computed using two-tails correlation at 95 % level of significance.

3 Results

3.1 Maize grain yield and yield components

Farmers' practice (July-planted maize sole cropping; control) had the lowest grain yield of 2.73 Mg ha^{-1} (Tab. 1). Grain yield was significantly highest in June-planted maize sole cropping (8.5 Mg ha^{-1}), followed by July-planted maize relay-cropping (4.68 Mg ha^{-1}). Similar trends were found for 100-seed-weight, ear length, seed number per ear, and HI, while maize aboveground biomass (AGB) was highest in July-planted maize relay-cropping (15.1 Mg ha^{-1}), followed by July-planted maize sole cropping (control; 13.5 Mg ha^{-1}) and June-planted maize sole cropping (12.9 Mg ha^{-1}). All

Table 1: *Grain yield, yield components, total above ground biomass (AGB) and harvest index as affected by cropping strategy. Data were collected during 2018 at Wang Thong district, Phitsanulok province, Thailand.*

Cropping strategy	*Grain yield ($Mg\,ha^{-1}$)*	*100-seed -weight (g)*	*Ear length (cm)*	*Seed number per ear*	*AGB ($Mg\,ha^{-1}$)*	*Harvest Index*
July-planted maize sole crop (control)	2.73±0.33c	17.7±1.0c	9.76±0.45c	183±13b	13.45±0.93	0.22±0.12c
July-planted maize relay crop	4.68±0.33b	25.9±1.0b	12.71±0.45b	219±13b	15.11±0.93	0.31±0.12b
June-planted maize sole crop	8.50±0.51a	35.3±1.6a	14.69±0.72a	322±20a	12.87±1.47	0.60±0.03a
F-test						
Cropping strategy (CS)	<0.05	<0.05	<0.05	<0.05	0.32ns	<0.05
Slope position (SP)	0.75ns	0.13ns	0.58ns	0.64ns	0.58ns	0.67ns
CS×SP	<0.05	0.44ns	<0.05	<0.05	<0.05	0.22ns

Note:ns=not significant at P≤ 0.05; values in the same column followed by different letters are significantly different for cropping strategy at P≤ 0.05.

Table 2: *Person's correlation between maize yield components as affected by cropping pattern.*

Yield components	*100-seed- weight*	*Ear length*	*Number of seeds per cop*
July-planted maize sole crop (control)			
Grain yield	0.71*	0.77*	0.85*
100-seed-weight		0.53*	0.40
Ear length			0.90*
July-planted maize relay crop			
Grain yield	0.71*	0.84*	0.93*
100-seed-weight		0.62*	0.42*
Ear length			0.76*
June-planted maize sole crop			
Grain yield	-0.83*	0.75*	0.81*
100-seed-weight		-0.87*	-0.99*
Ear length			0.86*

Note: * = significant at P≤ 0.05

yield components showed significant differences between treatments.

Significant differences found for maize grain yield and yield components together with the lacking significant impact of slope position indicated that maize yield was influenced by sowing time and relay-cropping, associated with weather differences during maize growth. Fig. 1 shows a period with extremely high temperatures (> 40 °C) from late August until mid of November. Hence, July-planted maize sole and relay-cropping treatments encountered a growth period with very high temperatures from 35 DAS until harvest, while June-planted maize sole cropping, planted 43 days earlier did not experience such a heat stress during its vegetative growth and only late in its generative growth. Additionally, the control and July-planted maize relay-cropping received much less precipitation during maize growth than June-planted maize sole cropping (508 mm vs. 950 mm).

Correlations between yield components indicated that patterns for both, maize sole crop and relay crop planted in July, were similar and positively correlated (Tab. 2). In contrast, grain yield and 100-seed-weight, 100-seed-weight and ear length, and 100-seed-weight and numbers of seed per cob of June-planted maize were negatively correlated. Correlations between 100-seed-weight and seeds number per ear of both July-planted maize treatments were weak (July-planted maize sole crop: $R^2 = 0.40$; July-planted maize relay crop: $R^2 = 0.42$). Maize relay crop, however, had often higher correlations than maize sole crop (grain yield and ear length: $R^2 = 0.84$); 100-seed-weight and ear length: $R^2 = 0.62$; grain yield and numbers of seed per cob: $R^2 = 0.93$), while June-planted maize sole crop had a strong negative correlation between 100-seed-weight and seed number per ear ($R^2 = 0.99$).

3.2 Nitrogen status of maize

Fig. 2 shows that both July-planted maize treatments had low NNI (≤1) values throughout the measuring period, indicating N deficiency in maize leaves. Especially in the relay cropping treatment, NNI values were significantly lower during early maize growth (0.6 at 27 DAS), probably due to competition with mungbeans for light suppressing growth of emerging maize plants during initial growth stages as mungbeans already had a height of 30 cm at maize sowing. (Suppl. Mat Fig. 2a). July-planted maize sole cropping, however, showed a N uptake close to the optimum range during maize early growth stages.

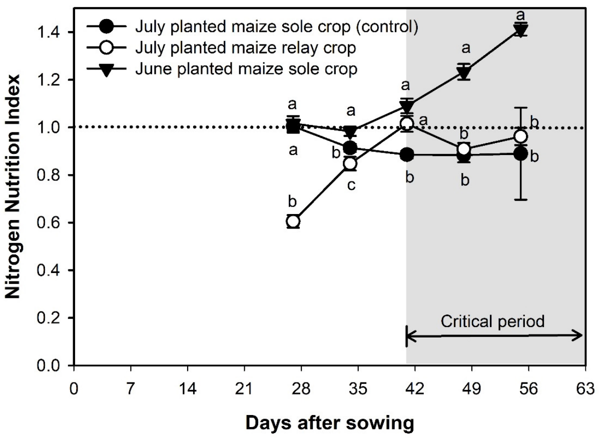

Fig. 2: *SPAD derived nitrogen status in maize leaves as affected by cropping strategy. A Nitrogen Nutrition Index (NNI) of 1 indicates sufficient N. Data were collected during 2018 at Wang Thong district, Phitsanulok province, Thailand.*

When heat and water stress occurred (~35 DAS), NNI values of both July-planted treatments dropped and values fell below the optimum range. In the control, NNI dropped even to 0.8, while relay cropping was able to maintain a higher N leaf status but still below the optimum range. June-planted maize sole cropping remained above optimum range of leaf N content in later growth stages, being significantly higher than the control at 56 DAS.

3.3 Water stress indicators

In June, soil moisture content was 13.4 Vol % at maize sowing and 15.7 Vol % at mungbean sowing, while soil moisture was 16.5 Vol % at maize sowing in July. Soil moisture patterns in the two July-planted maize treatments revealed that mungbean-maize relay-cropping used a higher amount of water compared to maize sole cropping (Fig. 3). During periods with higher rainfall distribution, soil moisture of both treatments was similarly depleted. Soil water depletion, however, increased much stronger in the relay-cropping treatment under unfavourable weather conditions, particularly when associated with periods of high-water demand by maize (50 and 60 DAS).

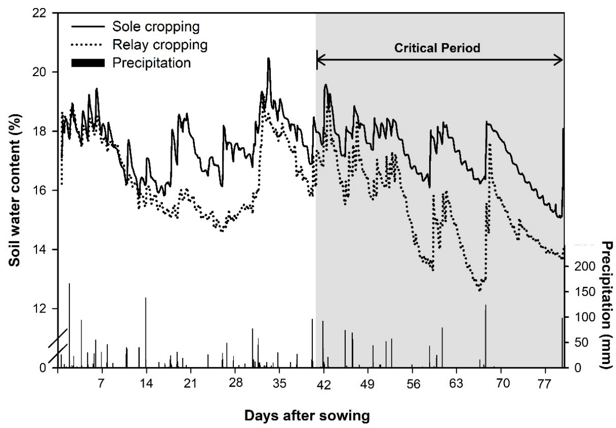

Fig. 3: *Soil water content of July-planted maize sole crop and maize relay crop. Data were collected during 2018 at Wang Thong district, Phitsanulok province, Thailand.*

Under lower ambient temperatures and more evenly distributed rainfall, stomatal conductance was not significantly different between both July-planted treatments (Fig. 4a). Under unfavourable weather conditions (heat/water stress during critical period), however, maize plants of the relay cropping treatment had a significantly higher potential to keep stomata open (320 mmol m^{-2} s^{-1}) than plants under sole cropping (100 mmol m^{-2} s^{-1}).

Stable isotope discrimination results support the findings that July-planted maize, regardless of sole or relay-cropping, suffered under the extreme weather conditions of 2018, while June-planted maize grew under less heat and more rain (Fig. 4b). Maize grain $\delta^{13}C$ value of June-planted maize sole cropped ($\delta^{13}C = -9.43$ ‰) was in the expected range of

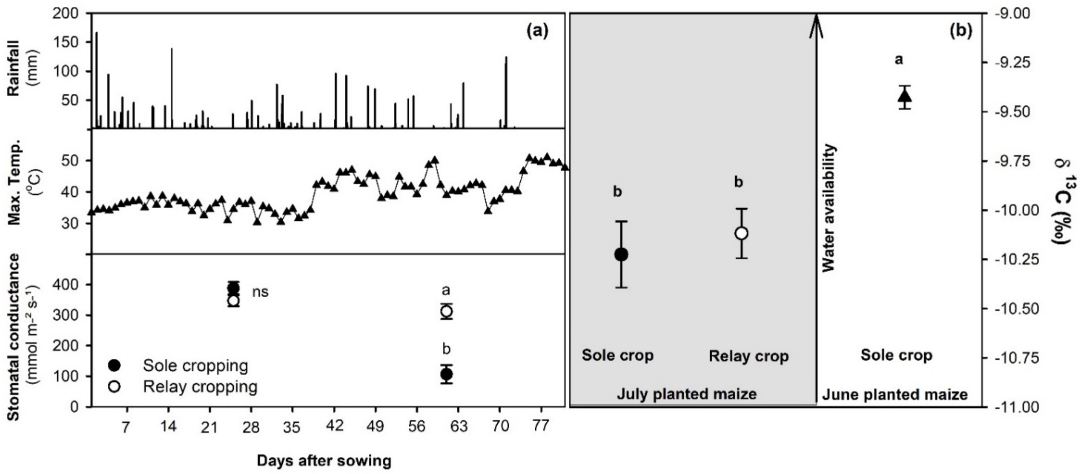

Fig. 4: *Indicators of heat and drought stress in maize sole and relay cropping: stomatal conductance (a) and δ13C isotope discrimination data of maize grains (b). Data were collected during 2018 at Wang Thong district, Phitsanulok province, Thailand.*
Note: Data points with different letters at the same sampling time indicate significant differences using LSD (P > 0.05); vertical bars = standard error (SE)

C_4 plants, indicating a higher water availability compared to both July-planted treatments whose grain δ^{13}C values were more negative, which means that maize experienced drought in these treatments. There were no significant differences between July-planted maize sole and relay-cropping. Nevertheless, July-planted maize relay cropped showed a slightly less negative value ($\delta^{13}C = -10.12$ ‰), indicating a lower impact of drought than the control (July-planted maize sole cropped : $\delta^{13}C = -10.23$ ‰).

4 Discussion

4.1 Heat and drought effects

Annual rainfall distribution is an important factor for crop growth and yield performance. In Thailand, maize is traditionally sown by mid of April until June, along with the start of the rainy season (Gerpacio & Pingali, 2007). Delays in the onset of the rainy period starting in the last decade urged famers to shift maize sowing to later periods of the rainy seasons. These delays cause temperature extremes, particularly during dry spells. According to Paengkaew *et al.* (2020), the heat index trend of Thailand is high (≥ 35 °C) during March to May, a common period without or little rainfall. Rainfall reduces heat by cloudiness (Schlesinger *et al.*, 2007), while dry spells during the rainy season increase the heat index. Monthly SPI values of 2017 and 2018 indicate that drought periods occurred during the late rainy season from August to October (Suppl. Mat. Fig. 1). This period is, hence, more likely to face heat stress than the early part of the rainy season.

Several studies indicated that high temperature led to large maize yield losses, even when maize encountered only short periods of high temperature during sensitive growth periods (e.g. Hawkins *et al.*, 2013). On the other side, various studies showed that irrigation or well distributed rainfall can reduce maximum temperature up to 7.5 °C due to cloudiness and a higher air humidity (Haddeland *et al.*, 2006; Mahmood *et al.*, 2006). The long-term trend of Thai temperature data (1970 until present) indicated that temperature extremes increasingly start occurring in the form of a higher number of warm days and nights or extended warm spells (Limjirakan & Limsakul, 2012). Therefore, either breeding or crop management efforts are urgently required to improve temperature resilience of maize production (Huey *et al.*, 2012).

In this study yield losses reached up to 60 %, when maize was hit by heat and water stress during grain yield formation stages as happened to July-planted, sole cropped maize, the current farmers' practice in the research area. Similar effects were reported by Wilhelm & Wartmann (2004). Nouri-Ganbalaniert *et al.* (2009) obtained a lower seed weight per plant and lower 100-seed-weight in years of high temperature and unfavourable distribution of precipitation as happened to the farmers' practice in this study. The sink-source relationship during grain-filling is of great importance for kernel setting (Borrás *et al.*, 2002). Water deficits, especially during pollination, influence this relationship (Setter *et al.*, 2001). The assimilate supply increases kernel setting by feeding sucrose to the reproductive organ when water deficits occur at pollination (McLaughlin & Boyer, 2004). A reduction of maize leaf area index (LAI) observed in both, July-planted maize sole and relay-cropping, decreased photosynthesis (data not shown, LAI was measured by using a non-destructive method, using a LP80 Inceptometer, Decagon Devices Inc., Pullman, Washington). This is a result of accelerated leaf senescence in consequence of a reduced activity of leaves due to the water deficit. This affected kernel setting negatively and reduced maize grain yield finally as also indicated by Li *et al.* (2018). Maize yield is mainly determined during a period of four to five weeks at silking. During this time, the crop growth rate significantly determines the number of kernel set (Otegui & Bonhomme, 1998), a key indicator of final maize grain yield (Edmeades *et al.*, 2017). This is why, this period is referred to as “critical” for maize yield determination with a high sensitivity to abiotic stress (Edmeades *et al.*, 2017). From our field study, it is evident that high temperatures during this critical period of maize led to a reduction in maize kernel setting as shown by significantly ($p < 0.05$) lower seed number per ear, when maize was planted in July compared to June-planted maize, which did not experience such a weather extreme. Similar large effects of high temperature on kernel setting and maize yield were reported by Rattalino *et al.* (2013) and Ordóñez *et al.* (2015). The negative impact is mainly driven by a reduced ovary fertilisation of pollinated spikelets that are exposed to temperature above 35 °C (Dupuis & Dumas, 1990). Other studies emphasised that the reduction in seed number was mainly due to kernel abortion, associated with high temperature during flowering (Rattalino *et al.*, 2013; Ordóñez *et al.*, 2015). Sowing maize earlier is an appropriate solution, if rainfall is evenly distributed or predictable; however, once rainfall is erratic and associated with sporadic heat waves, other measures need to be considered, e.g. relay-cropping or staggered planting. An *ex-ante* analysis using a modelling approach may help to test their suitability and identify the best practice under variable environmental conditions. Pansak *et al.* (2010) used the Water, Nutrient and Light Capture in Agroforestry Systems model in Northeast Thailand to assess soil conservation measure, while Hussain *et al.* (2016) used the same model in West Thailand to model resource competition at the soil-crop-hedge interface. Both studies indicated the added value of such an approach and may allow an *ex-ante* testing of a wide range of cropping options.

At harvest, yield components of maize are usually strongly correlated between each component. Stress, however, may reduce these relationships. In this study, July-planted maize sole and relay-cropping had to cope with temperatures above 40 °C, associated with poor rainfall, during the critical period of maize yield formation, while June-planted sole cropped maize did not face such conditions. This led to weaker relationships between yield components for both July-planted maize, while having stronger correlations in June-planted maize. Thus, planting maize earlier than farmers’ practice led to an almost three times higher yield in the June-planted maize sole cropping treatment than in July-planted maize sole cropping. Under relay-cropping, however, July-planted maize was still able to produce a 70 % higher yield than the control. This points to the necessity of considering alternative sowing dates and adapting crop management, when the likelihood of heat and drought stress during sensitive generative growth phases of maize starts to consolidate or even to increase. Total rainfall over the last ten years did not differ much in the area but the distribution did (Thai Meteorological Department, 2019). Rainfall distribution was better during the maize cropping season when sown in June, while sowing maize in July led to strongly reduced water availability from 60 DAS onwards (Fig. 1). This indicates that June became the wettest month in recent years, further pointing to the need to adapt planting dates to avoid stress during sensitive growth stages of maize.

4.2 Relay-cropping effects

The results of this study revealed that July-planted maize-mungbean relay-cropping partly mitigated negative effects of drought and heat during critical periods of maize yield formation compared to the current farmers’ practice of sole cropping. Maize yield under relay-cropping performed better than sole cropping. In addition, mungbean produced 0.71 $\mathrm{Mg\,ha^{-1}}$ of grain and 12.47 $\mathrm{Mg\,ha^{-1}}$ of above ground biomass (data not shown). Similar observations of higher maize grain yield of a relay crop over sole cropping was reported by Raseduzzaman & Jensen (2017). They found a significant yield stabilizing effect of cereal-grain legume intercropping under various levels of drought and high temperature compared to sole cropping. Gou *et al.* (2017) studied yield gaps and gains of maize-wheat intercropping. Their results indicated that maize-wheat intercropping had a positive effect on maize grain yields compared to sole cropping. Brooker (2015) also stated that intercropping had the ability to sustain food production under low inputs in various environments. Our findings show that mungbean-maize relay-cropping did not only stabilize maize yield under unfavourable weather condition, but it led to a higher maize AGB production compared to sole cropping, possibly associated with biological N fixation through mungbeans and a release of N after mungbeans were mulched in the relay-cropping system. The contrasting maize leaf N uptake patterns of both July-planted maize cropping systems 42 DAS with higher leaf NNI of relay-cropped maize, point to this effect, while there were signs of N competition at 28 DAS. A five-year study of Roldán *et al.* (2007) indicated that total SOC and total soil N, microbial biomass and soil enzyme activity in legume relay cropping were significantly higher than in maize sole cropping.

Mungbean residues as a soil cover may have improved soil water availability for maize by both, increasing dew water and reducing evaporation (Van Donk *et al.*, 2010). Stumpp *et al.* (2009) observed smaller water fluxes and less drainage in the soil under maize intercropping compared to sole cropping. On the other hand, soil cover has a direct impact on soil temperature in dry and hot environments. Our study indicates that 60 % of soil was covered by mungbean residues, creating a more favourable microclimate for maize growth. Under such conditions, maize relay cropping can still maintain translocation of nutrients and water from the roots to plant organs as indicated by stomatal conductance and leaf N uptake, while maize sole cropping was not able to keep stomata open under heat and drought stress. This also led to the higher observed soil water use in relay-cropping and facilitated higher assimilation rates as indicated by the higher stomatal conductance.

Competition for light during early growth of maize may have had a negative impact on leaf N uptake as observed in mungbean-maize relay-cropping (Fig. 2). Particularly prior to mungbean harvest, maize had a low gas exchange (Fig. 4a) through its transpiration, leading to a low N transfer from the soil to the leaf (Hofstra & Hesketh, 1969) and probably along with N competition between both species. After mungbean harvest, maize was able to take up more N than before, due to decomposing legume residues and roots, reaching, at least partly, higher SPAD N values than maize sole cropping. Cereal-legume intercropping fosters a higher nutrient use efficiency and lead to higher N uptake in intercrops compared to sole cropping as indicated by Ananthi *et al.* (2017), Zhang *et al.* (2015) and Li *et al.* (2018), while Zhang *et al.* (2008) observed a higher amount of N uptake in sole cropping than intercropping. In our experiment, the δ^{15}N values of July-planted maize were slightly higher under sole cropping (6.9 ‰) than under relay-cropping (6.8 ‰), possibly pointing to a positive mungbean effect on N uptake by maize.

5 Conclusions

Heat and drought conditions during critical periods of maize growth had a major impact on reproductive processes of maize. Maize planted in July showed, regardless of sole or relay-cropping, low grain formation and yields as consequence of adverse weather conditions. However, July-planted maize relay-cropping produced higher AGB than July-planted maize sole cropping and early planting of maize in June. Despite unfavourable weather conditions maize was, at least partly, able to compensate for such effects when relayed cropped, achieving a higher yield compared to maize sole cropping. A better timing of mungbean sowing when intercropped might have further reduced competition, fostering maize resilience. June-planted maize sole cropping, however, was fully able to escape such a critical phase and achieved the highest grain yield; the likelihood of insufficient rain after early rains needs, however, to be considered.

Both early planting of maize and/or relay-cropping with legumes are suitable coping strategies for heat- and drought-prone regions. The positive response of early planting and legume relay-cropping offers the opportunity of having a short-duration crop as sequential crop, providing an additional source of protein for humans and fostering crop diversification on-site.

Further studies are needed testing strategies to cope with climate change; e.g. mulching and green manuring to sustain soil organic matter. A modelling approach may help to identify coping strategies faster. Established at institutional level, and together with improved weather forecast, it will allow informed decision-making, particularly in areas prone to weather extremes. This may lead to a win-win situation for farmers, food security and the environment due to an enhanced sustainability of this cropping system.

Supplement

The supplement related to this article is available online on the same landing page at: https://doi.org/10.17170/kobra-202104133652 .

Conflict of interest

The authors declare that they have no conflict of interest.

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